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DETERMINATION OF THE EFFECTS OF DEFOCUS AND INFORMATION CONTENT--ETC(U)
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FINAL REPORT ON OPTICAL POWER SPECTRUM ANALYSIS

DETERMINATION OF THE EFFECTS OF DEFOCUS AND INFORMATION CONTENT

LEVEL II

by

R. R. Shannon

and S. Sagan

May 1978

Prepared for the
Space and Missile Systems Organization
Air Force Systems Command
Los Angeles Air Force Station, California
Under contract F04701-77-C-0059

Optical Sciences Center
University of Arizona
Tucson, Arizona 85721

This final report was submitted by the Optical Sciences Center, University of Arizona, Tucson, Arizona 85721, under contract F04701-77-C-0059 with the USAF Hq Space Division, Los Angeles, CA 90009. This report has been reviewed and cleared for open publication and/or public release by the Public Affairs Office (PAS) in accordance with AFR 190-17 and DODD 5230.9. There is no objection to unlimited distribution of this report to the public at large, or by DTIC to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved for publication.

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The concept of signal-to-noise power spectrum description of photographic imagery is extended to include transfer function losses and information content. A coherent optical processor is used for quantifying image content. Experiments show that theoretical predictions are verified.

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1. REVIEW OF THE OPTICAL POWER SPECTRUM ANALYSIS (OPS) CONCEPT

The determination of the objective level of quality or information content of technical photography is a subject of much interest. The use of specific targets for the production of numeric data, such as resolution or modulation transfer factor, is applicable only in cases where the original object is available for attaching a particular target. In many cases the desired general image description must be obtained from the natural imagery collected on the photographic negative. The use of a coherent optical processor for carrying out this measurement is a useful approach. Such applications are not novel, in that several authors have reported on this approach.[1]

In the Shannon and Cheatham work,[1] a method of describing the OPS characteristics by use of a "signal-to-noise power spectrum" method was developed. This concept, referred to as the SNPS function, succeeded in compressing the huge dynamic range of the observed image signal and the photographic and processor noise into a relatively simple function. The shape of this function with respect to spatial frequency was determined by the spectral content of the image, and would be useful as an index of image quality or image information content. The work being reported here is directed toward the implementation of that approach, and shows that successful application of the technique is possible.

The method of measurement is illustrated in Fig. 1. A conventional coherent optical Fourier analyzer is used to examine the photographic transparency placed in the aperture. The diffraction pattern produced at the

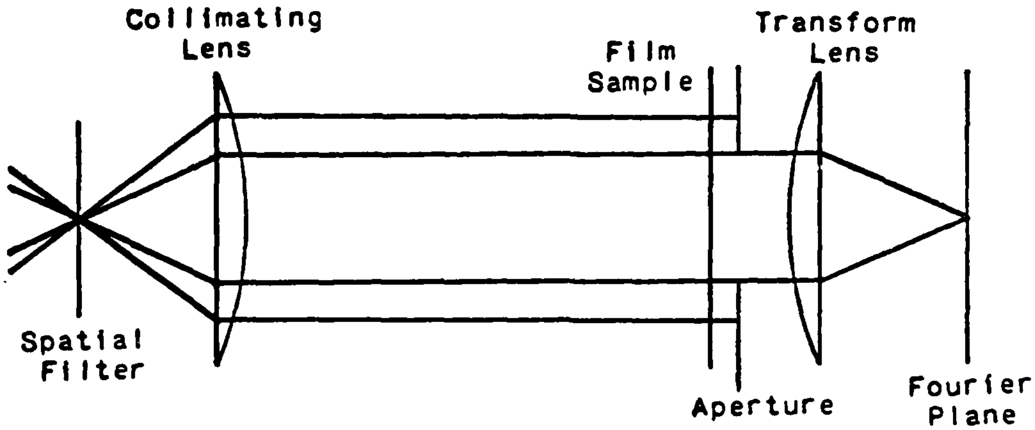


Fig. 1. Coherent optical processor diagram.

output plane is then a Fourier transform of the amplitude distribution within the aperture. This can be shown to be related to the power spectrum of the intensity transmission distribution within the aperture, as long as some reasonable restrictions are met. The previous report[1] shows that these are met in most cases of interest. The important point to be examined in this report is the extent to which the power spectrum is dependent on the image content and on some simple aberrations of the imaging system used to acquire the imagery.

The transmittance distribution for a photographic transparency is given by $f(x)$, where x is a two-dimensional variable. The function may be described by a Fourier transform frequency function $F(N)$, where N is a two-dimensional spatial frequency variable. The power spectrum is then given by

$$W(N) = |F(N)|^2 .$$

Several important relationships hold between the power spectrum and other functions describing the statistics of the image or noise content on

the image plane. A presumption can be made that the signal to be measured and the noise are generally of "low" amplitude. Then the imaging process yields a case of additive signal, s, and noise, n. That is, the content of the transparency can be described by

$$f(x) \;=\; s(x) + n(x),$$

where the two functions are assumed to be statistically independent and stationary. Then

$$W(\nu) \;=\; P(\nu) + N(\nu),$$

where the P and N functions are the power spectra of the image and the noise processes.

The above functions were shown in the previous report[1] to be applicable to the photographic imaging situation as long as the modulation contrast of either function did not exceed about 0.80. The nonlinearities of the process were generally ignored under the conditions of measurement, although some comments on this will be made later in this report. This conclusion is supported by the experimental results both in this study and the previous one.

In the additive noise case, the information capacity of the photographic system can be defined in terms of the power spectral distributions as

$$I \;=\; 2\pi \int \{\log_2\,[1+P(\nu)/N(\nu)]RdR\}$$

evaluated over the spatial frequency region of interest. The ratio of power spectra within the argument of the integral is the SNPS value for the particular spatial frequency of interest.

The determination of the SNPS function from the measured diffraction pattern data is accomplished by using two separate measurements, one with the sample of interest, and the second with a sample of the same type of material which has been uniformly exposed and processed to a density level at about the average of the densities of the test sample. The measured OPS curve of the second uniform sample is scaled to match the OPS of the test sample at the high spatial frequencies beyond the region where the test sample is known to contain image spatial frequency information. This is possible because of the specific upper spatial frequency limit of optical imaging systems. If we define the two measurements of the OPS by $M1$ and $M2$ for each spatial frequency band, and define A as the above described adjustment constant, then

$$\mathrm{SNPS}(\nu) = P(\nu)/N(\nu) = [M1(\nu)/A*M2(\nu)] - 1,$$

where the exact process of computation and measurement is described in reference 1.

The above theoretical and experimental observations served as the starting point for the work reported here. The experimental work was carried out by Mr. Steven Sagan as a portion of the requirements for an MS degree in optical sciences.

2. SUMMARY OF WORK DONE

The purpose of this work was to investigate the applicability of the SNPS approach to a number of different actual photographic scenes and images. Therefore the first step was the selection of appropriate types of objects. The principal application of OPS techniques to date has been in the analysis of aerial photographic scenes. This has been a consequence both of the fact that the need and the funding have arisen from this area of photography. In this study it was desired to obtain input material that would combine the objectivity and detail recording of aerial photography with the wider applicability to scenic photography. It was necessary to select scene material for large amounts of random scene content, hopefully with a wide and reasonably flat spectral content. The chosen scenes should be readily accessible for multiple takes of photography, and should provide scenic material which would allow some subjective evaluation if the occasion arose. (As it developed, no subjective evaluation was carried out on the pictures, it being deemed outside of the scope of this study.)

The choice of the scenes also should permit several samples of spectra to be measured on each scene so that some reasonable level of averaging or statistical significance could be assigned to the results. The acquisition of the photographic material was accomplished using an ordinary 35-mm camera, a Canon FD fitted with a 50-mm, $f/1.8$ lens. The lens generally was used with a significant reduction in aperture, from $f/8$ through $f/16$, so the lens could be considered as being limited by diffraction over the entire field for the purpose of this experiment. The use of small numerical apertures

maintained the upper cutoff frequency of the imagery within the convenient 100 cycle per millimeter range of the coherent processor being used.

The photographic materials used were Kodak Plus-X and Pan-X, which were processed to low, medium, or high contrast in D-76 developer.

The coherent processor was of conventional design with a Recognition Systems, Incorporated sensor. The use of a He-Ne laser and a 200-mm focal length transform lens yielded a spatial frequency cutoff at about 100 cycles per millimeter, with 32 annular frequency sampling rings in the spatial frequency plane. The details of this type of processor are available in reference 1. The method of averaging noise, calibrating the detector and electronics, and processing the data followed precisely the same approach as that in reference 1.

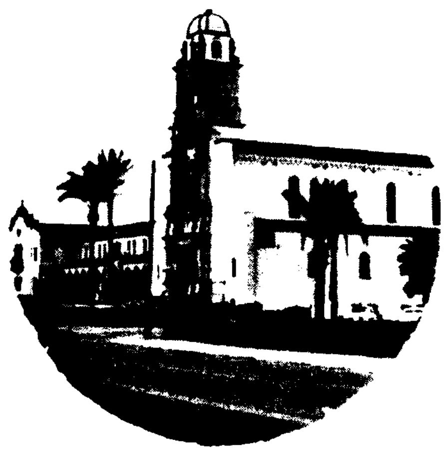
The choice of the "random" scenes was made by examining a number of different architectural types. The final choice resulted in the use of four scenes near the University, chosen for their accessibility, lack of changing features (such as automobiles in a parking lot would produce), and large amount of distributed high-frequency content. These scenes are shown in Fig. 2. All of the photography was collected within a short period of time on a specific day for each object, in order to avoid shadow changes of any significance. For each object, a number of focal positions was chosen to permit investigation of the sensitivity of the SNPS measurement to changes in the optical transfer function.

In addition to the above natural architectural scenes, two random objects with different spatial frequency contents were produced by photographing assemblies of coarse and fine gravel beds. These latter scenes

A. Arizona State Museum

B. Old Main

C. Mission Church
(View One)



D. Mission Church
(View Two)

Fig. 2. Random scenes on Pan-X.

would allow comparison of the natural scene results with a totally random, but visually boring, scene.

Figure 3 shows the SNPS of the natural scenes. The similarity of the spectra is due to the similarity of the lens transfer functions used in producing the imagery; the difference is due to the scene differences. Figure 4 shows SNPS data for the random pebble scenes. The higher value is indicative of the much higher spectral content of the random scenes.

The shape of the SNPS curve is characteristic of the form of the data taken. Figure 5 shows a signal, or signal plus background and noise spectrum, for the processor along with a signal plus background. The large dynamic range can be noted, as well as the fact that the processor noise, due to scattering in the optics, is dominant at the lowest frequencies, whereas the photographic grain noise contributes to the wide angle scattering which is dominant at the high frequency end. Therefore, the photographic noise can be properly corrected by scaling the magnitude using the difference between the two spectra at the high frequency end as a guide. The low frequency end remains set at unity for both spectra, but the shape difference between the two curves scales the SNPS values at the low frequency end. Therefore, the shape of the SNPS curve will be dependent to some extent on the quality of the processor at the zero frequency end. Care must be taken in constructing the processor optics that the narrow angle scattering region does not intrude a significant extent into the spatial frequency region which is to be measured. Comparison of an "open gate" spectrum with a flashed density sample will give an indication of the effect to be expected. In all of the analyses carried out in this experiment, the low frequency region in which the effect

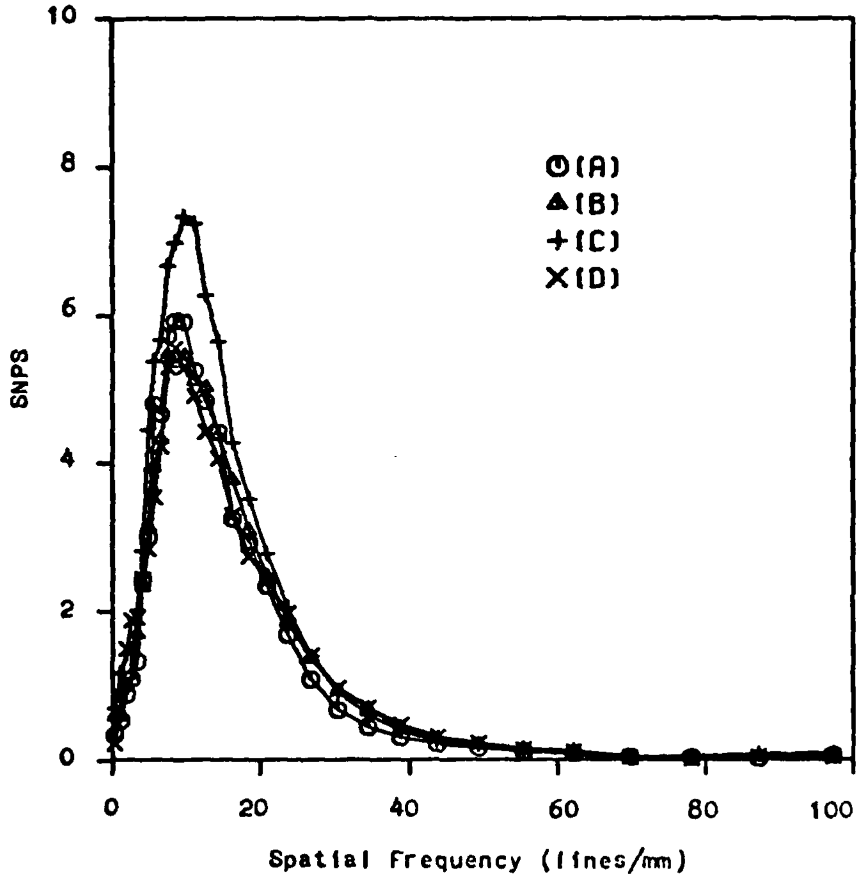


Fig. 3. SNPS of the random scenes in Fig. 2.

(A) Arizona State Museum
(B) Old Main
(C) Mission Church (view one)
(D) Mission Church (view two)

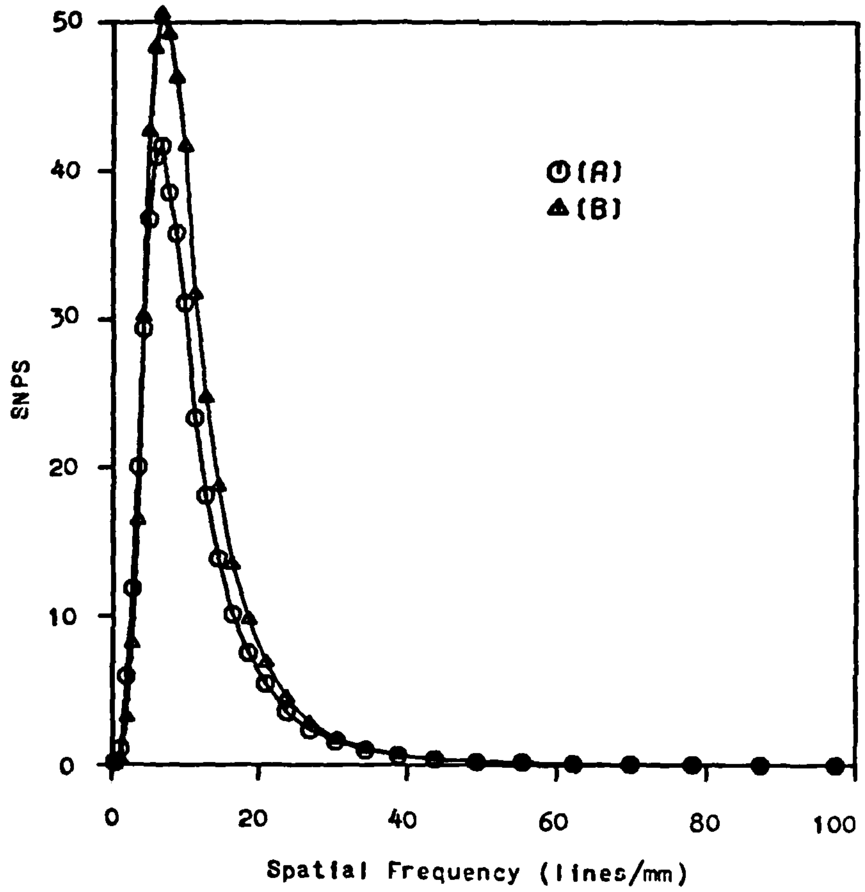


Fig. 4. SNPS of the random distribution of pebbles.

(A) Medium size pebbles
(B) Small size pebbles

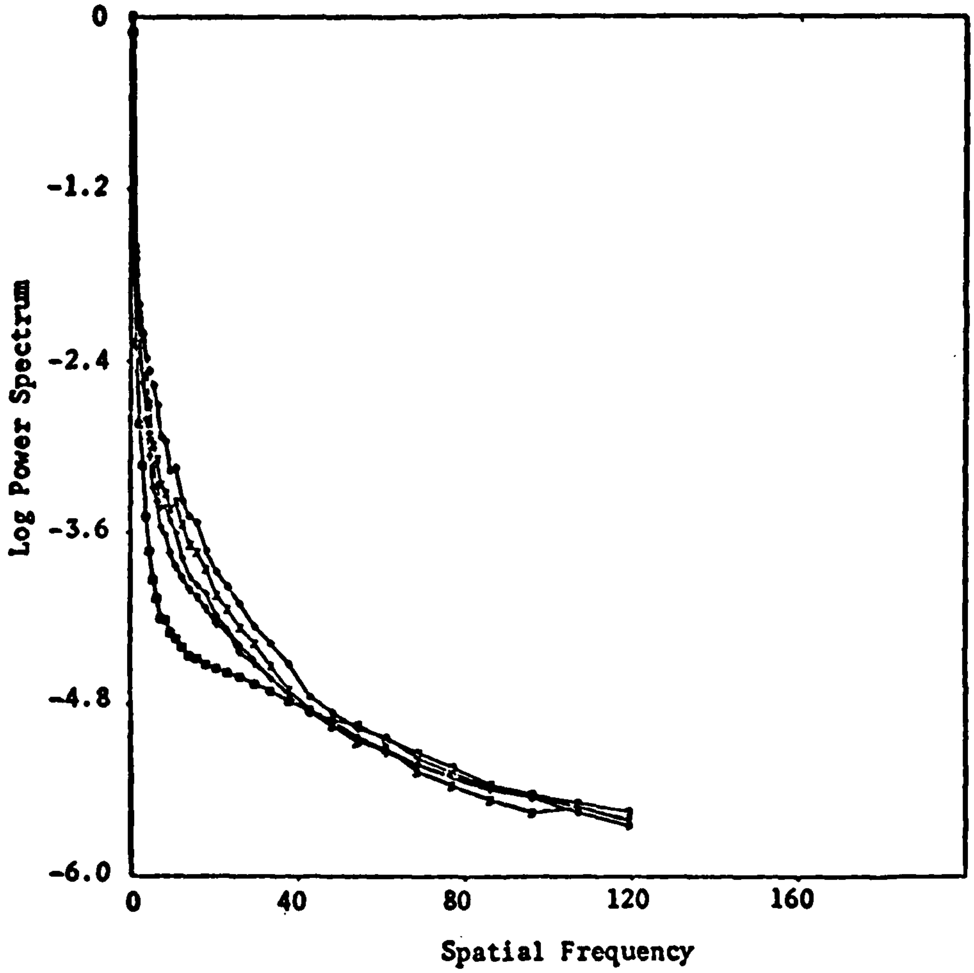


Fig. 5. Log power spectrum vs spatial frequency for the calibrated images on 1414 film and the 3414 noise curve (from ref. 1).

□ 3414 noise curve
◇ 3.4:1 contrast image
♦ 2.3:1 contrast image
+ 1.7:1 contrast image
↑ 1.2:1 contrast image

is prominent lies below 5 cycles per millimeter, whereas the peak of the SNPS spectrum is in the region between 15 and 40 cycles per millimeter.

The above described low-frequency effect does produce a possible distortion of the information capacity data to be discussed later, but is actually quite small, estimated as less than 10%. Since relative values of this function were to be compared, this effect was considered to be negligible. Later data to be presented on the effect of defocus, as an example of taking lens aberrations, on the SNPS, showed the above effect to be negligible.

Now let us return to the question of the effect of sample size (that is aperture diameter of the processor) on the SNPS. Figure 6 shows the effect of changing the sampling aperture size on the SNPS of the "Old Main" image. Figure 7 shows the effect of placing the smallest aperture (6 mm) in different locations on the image. In both cases, some difference can be expected because the image frame is naturally not filled with imagery. Figure 8 shows an average and deviation of the spectral samples that were obtained for this image. A second example is the "Mission Church" scene. Figures 9 through 11 show that the variation is indeed scene content dependent.

To compare the two different methods of obtaining an average SNPS, Figs. 12 and 13 are comparisons of the SNPS obtained with small and large apertures. It is clear from these figures that an adequate average is obtained by a single parallel optical measurement with a large sampling aperture. The observations apply to these scenes, but it is obvious that similar conclusions will apply to any photographic record.

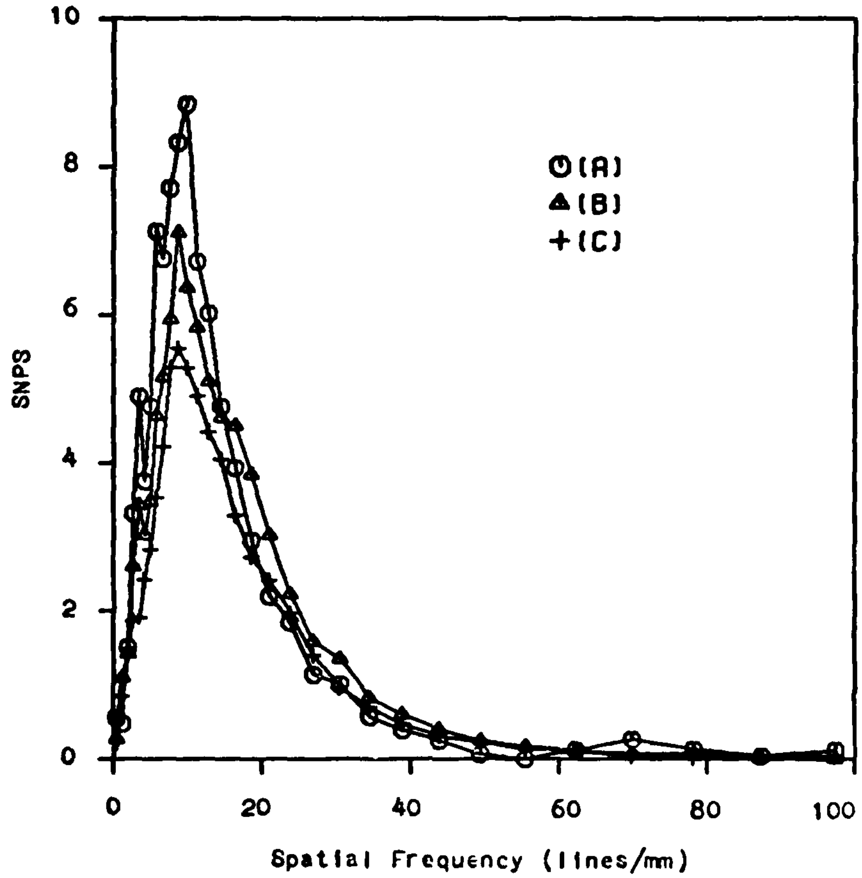


Fig. 6. Effect of sampling aperture size on the SNPS of the random scene in Fig. 2D.

(A) 6.0 mm
(B) 11.5 mm
(C) 20.0 mm

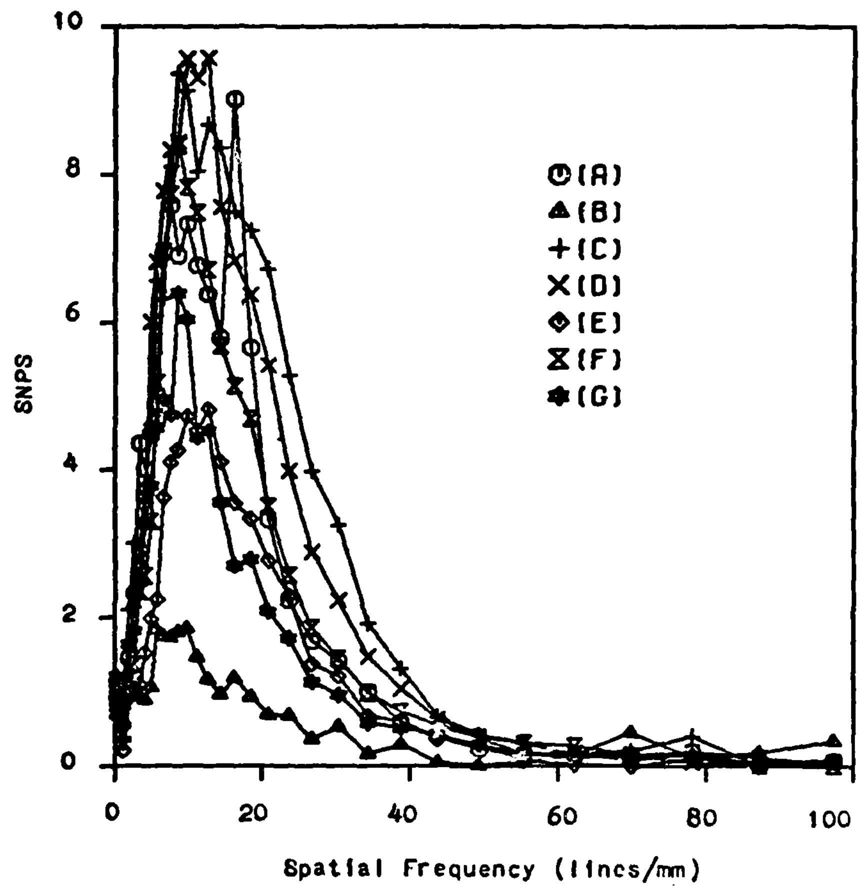


Fig. 7. Effect of aperture placement on the SNPS and information capacity of the random scene in Fig. 2B.

The curves (A-B) correspond to the 6-mm aperture placements in Fig. 6
(A) $I = 1.29 \times 10^4$ bits/mm^2
(B) $I = 1.16 \times 10^4$ bits/mm^2
(C) $I = 2.09 \times 10^4$ bits/mm^2
(D) $I = 1.81 \times 10^4$ bits/mm^2
(E) $I = 1.17 \times 10^4$ bits/mm^2
(F) $I = 1.61 \times 10^4$ bits/mm^2
(G) $I = 1.19 \times 10^4$ bits/mm^2

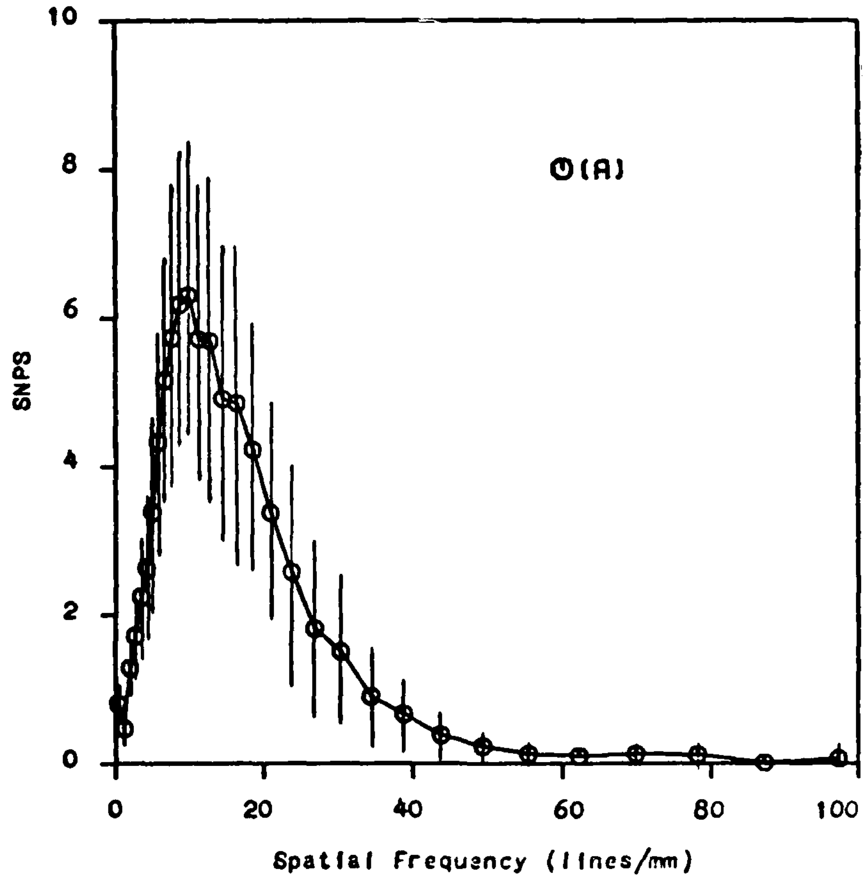


Fig. 8. Mean and standard deviation of the SNPS and information capacities of Fig. 7.

(A) with $\overline{I}$ = 1.42 × 10^4 bits/mm^2 and σ_I = 3.15 × 10^3 bits/mm^2

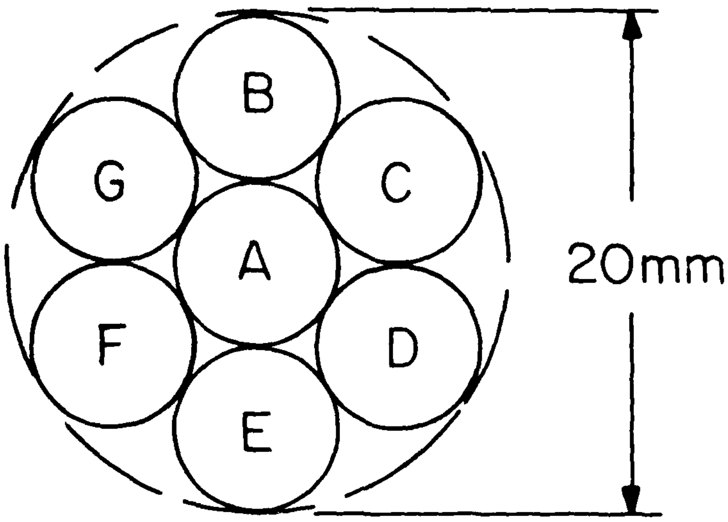


Fig. 9. Hexapolar sampling pattern.

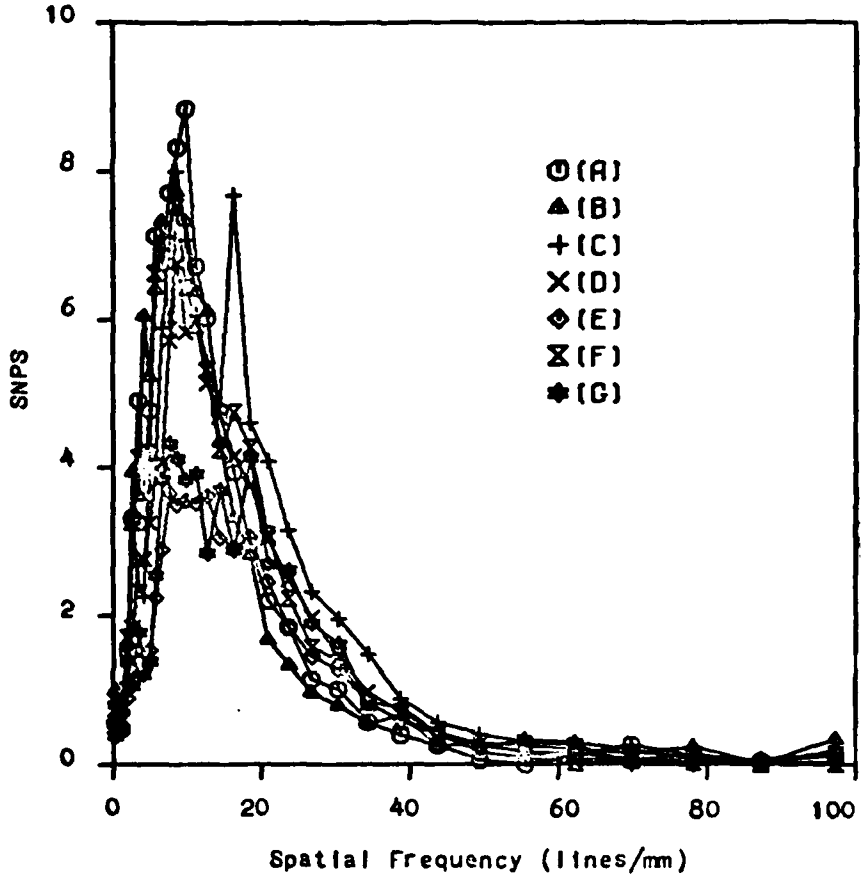


Fig. 10. Effect of aperture placement on the SNPS and information capacity of the random scene in Fig. 2D.

The curves (A-G) correspond to the 6-mm aperture placements in Fig. 6.

(A) $I = 1.17 \times 10^4$ bits/mm^2
(B) $I = 1.59 \times 10^4$ bits/mm^2
(C) $I = 1.70 \times 10^4$ bits/mm^2
(D) $I = 1.23 \times 10^4$ bits/mm^2
(E) $I = 1.23 \times 10^4$ bits/mm^2
(F) $I = 1.03 \times 10^4$ bits/mm^2
(G) $I = 1.49 \times 10^4$ bits/mm^2

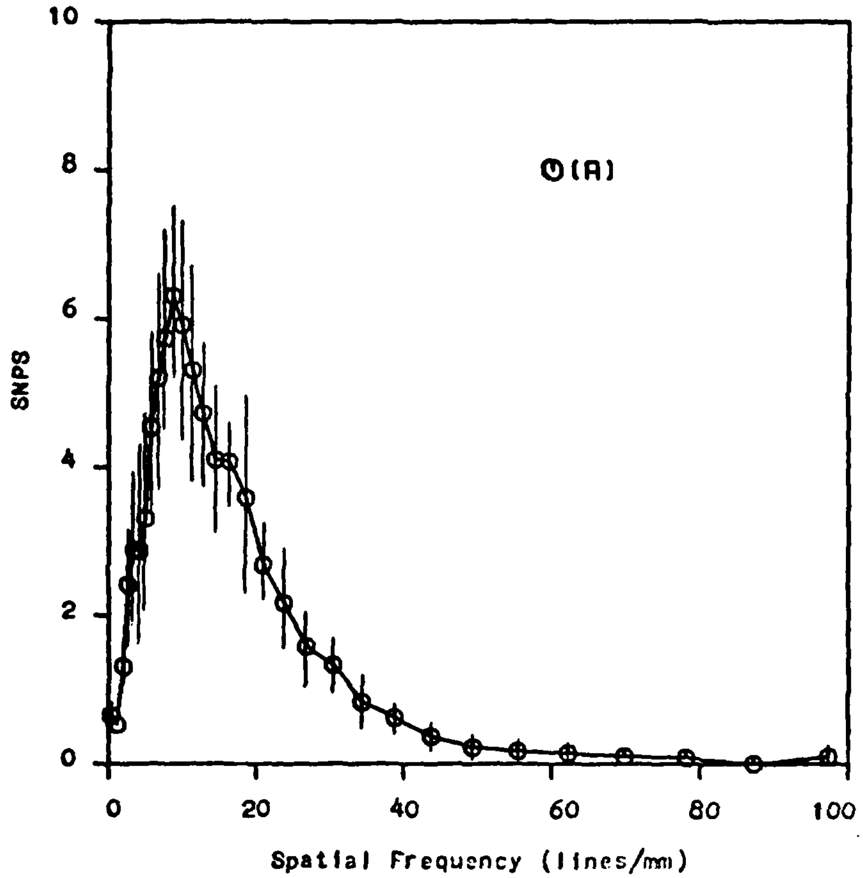


Fig. 11. Mean and standard deviation of the SNPS and information capacities of Fig. 8.

(A) with $\overline{I} = 1.33 \times 10^4$ bits/mm^2 and $\sigma_I = 2.44 \times 10^3$ bits/mm^2

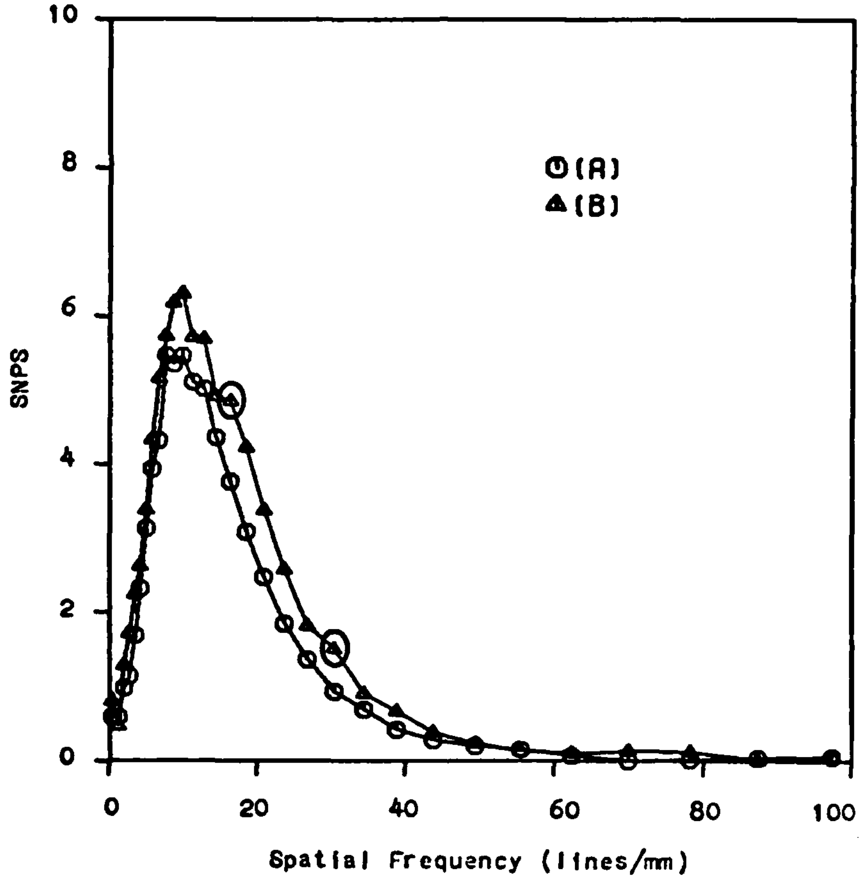


Fig. 12. Averaging effect of the coherent optical processor aperture for the random scene in Fig. 2B.

(A) 20-mm measurement
(B) Average of the seven 6-mm measurements

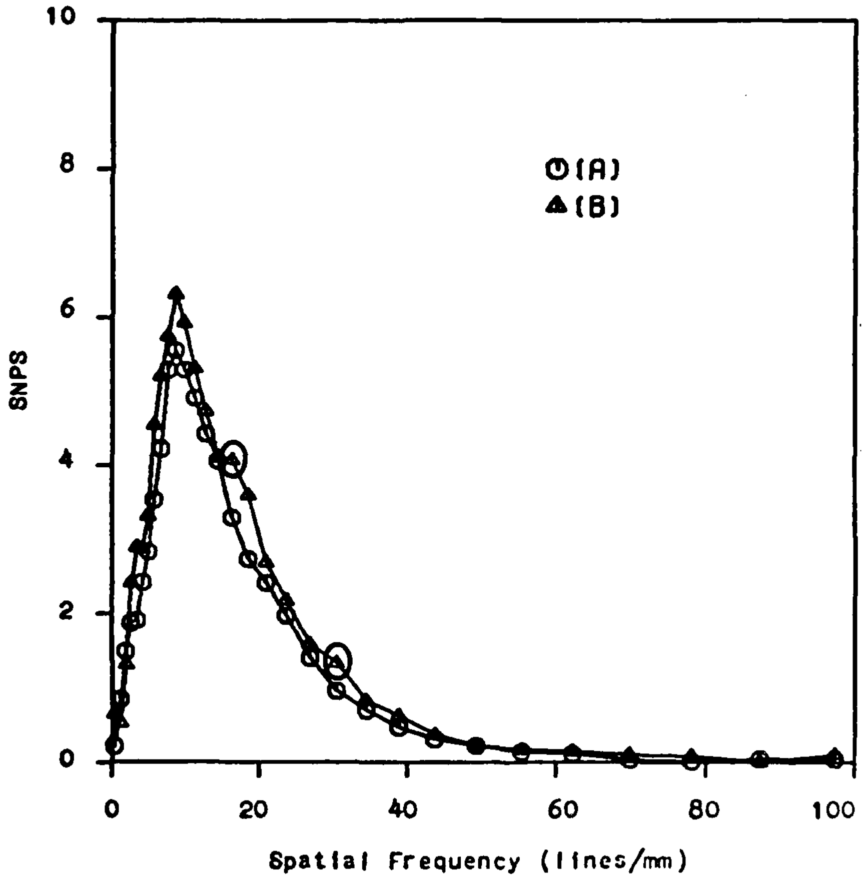


Fig. 13. Averaging effect of the coherent optical processor aperture for the random scene in Fig. 2D.

(A) 20-mm measurement
(B) Average of the seven 6-mm measurements

Reference to Sagan's thesis[2] will show several other examples of measurements that were made to indicate the effect of development contrast and object form on the SNPS. Some of these were intended to provide a comparison with the referenced prior work by Cheatham.[1] Such comparisons were found to provide very good agreement with prior work. This gives confidence that the techniques are independent of the particular experimenter or processor being used. The measurements in which the development time was varied in order to provide a variation in image contrast showed that consistency of shape of the curves was obtained in most cases.

The effect of defocusing on the SNPS was also measured, and compared with theoretical values. Figure 14 is one example of the many samples reported in Sagan's thesis, and shows the effect on the SNPS when differing focus positions are used in the picture-taking step. Figure 15 is typical of the agreement noted between the experimental SNPS values and theoretical values predicted by using the zero focus error values of SNPS as a normalization method.

For the theoretical comparison, lens transfer function values were calculated for the various amounts of defocus. The zero focus transfer function was used to correct the measured SNPS values to an effective object spectrum. These corrected values were then multiplied by the defocus transfer function values to obtain the theoretical values for the SNPS. (In fact, adjustment by the ratio of the two transfer functions will do.) The agreement is seen to be quite good. In principle, measurement of the SNPS could be used as a technique for determining the optical transfer function of the taking lens, if the basic form of the object spectrum were known. This is perhaps evident, but has not been demonstrated experimentally in any prior work.

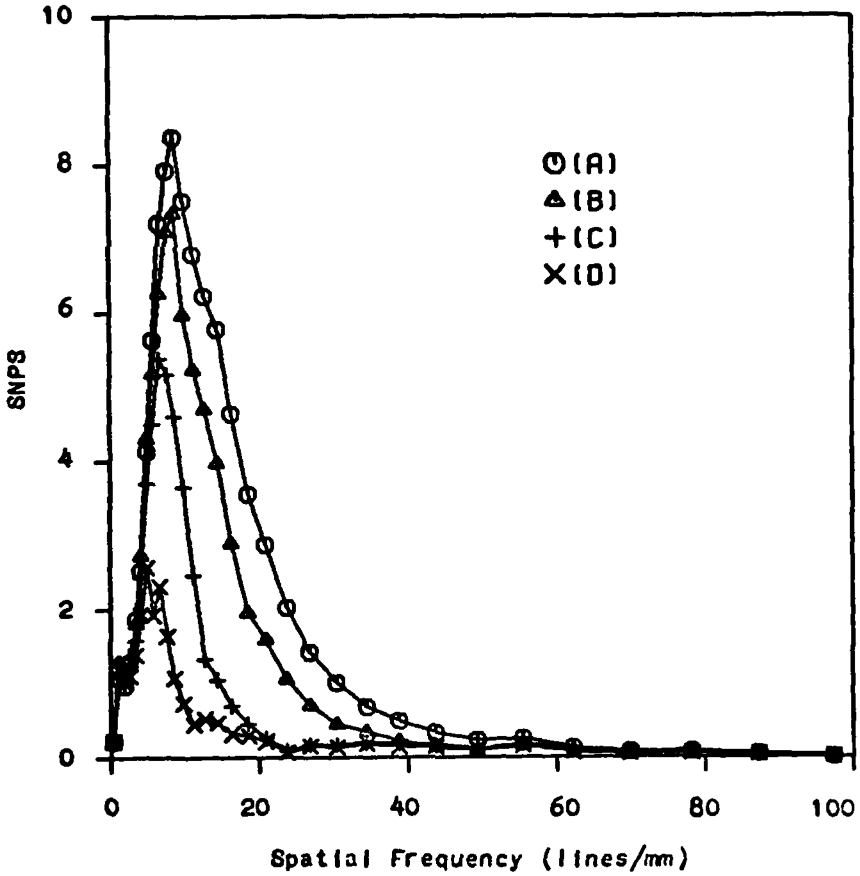


Fig. 14. Effect of defocus (Δ) on the SNPS of the medium contrast *f*/8 Pan-X samples.

(A) Δ = 0.0000
(B) Δ = 3.5690
(C) Δ = 7.1740
(D) Δ = 12.0384

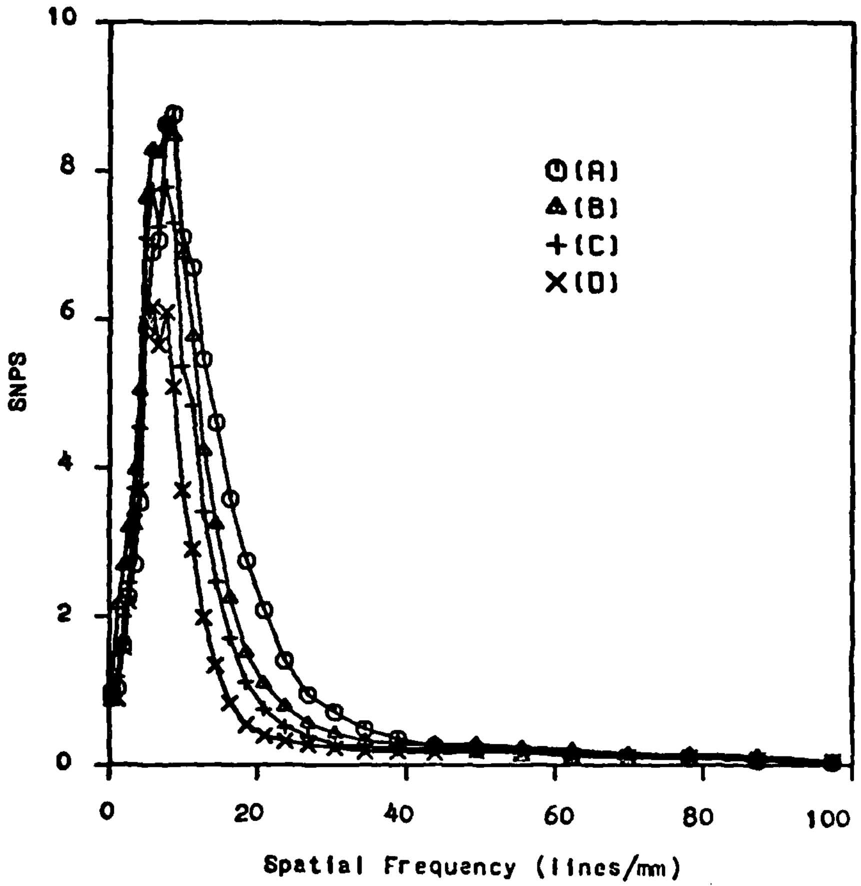


Fig. 15. Effect of defocus (Δ) on the SNPS of the high contrast *f*/16 Pan-X samples

(A) Δ = 0.0000
(B) Δ = 0.8922 (bad curve)
(C) Δ = 1.7935
(D) Δ = 3.0094

The SNPS provides a good detailed measurement of the spectral characteristics of the photographic imagery. There are other measures of the imagery that may be of interest in attempting to use a summary measure of the image content. One of these is the information capacity or information content of the image. This is a technical measure of the amount of information that may be stored in the image. The assumptions stated in the introduction about the additive character of the noise and the range of signal contrasts are applicable here. The quasilinear behavior of the SNPS functions in the presence of defocus aberrations, as well as the aperture size averaging properties of the measurement process indicate that the SNPS measurement does satisfy the necessary linear properties to be used in constructing an information capacity value. The measurement of power spectra does not, of course, include data about intersymbol or interpixel constraints that will affect the actual information content in the image. This method of measurement can only describe the maximum level of information in bits per unit area that can be obtained from an object with no interpixel correlation characteristics. This does place an upper limit on the information that could be stored in the image.

The calculation proceeds by use of the integral over the base two logarithm of the SNPS, summed over the two-dimensional spatial frequency region of interest. In this work it was found that different values were obtained for the information capacity if the measurement spatial frequency bandwidth was used for the integration, or if the known upper spatial frequency cutoff of the imaging lens was used. The difference is obviously due to the inclusion of some photographic grain noise that appears to provide

additional information bandwidth in the measurement of the image OPS. This effect is consistent with the meaning of information as independent of the nature of the object.

When the correction for the known spatial frequency cutoff of the lens is included, summary results as shown in Figs. 16 and 17 are obtained. These figures indicate a comparison of the measured SNPS values with theoretical values obtained from the defocus transfer functions as described before. The ordinate is in units of bits per square millimeter, and indicated information capacities 1200 to 1500 bits per square millimeter, diminished to as low as 500 bits per square millimeter for the amounts of defocusing chosen. These numbers are in fact quite reasonable. The agreement between the measured and theoretical values is, as expected, good because of the good fit observed between the measured and theoretical SNPS curves. For this reason, it was not seen necessary to evaluate more than one of the natural scenes in this manner.

One caution; the values of information capacity do include some losses due to the removal of processor noise at low frequencies. No attempt was made in this study to correct for this effect, but it could in principle be done by improvements in the scattering characteristics of the processor.

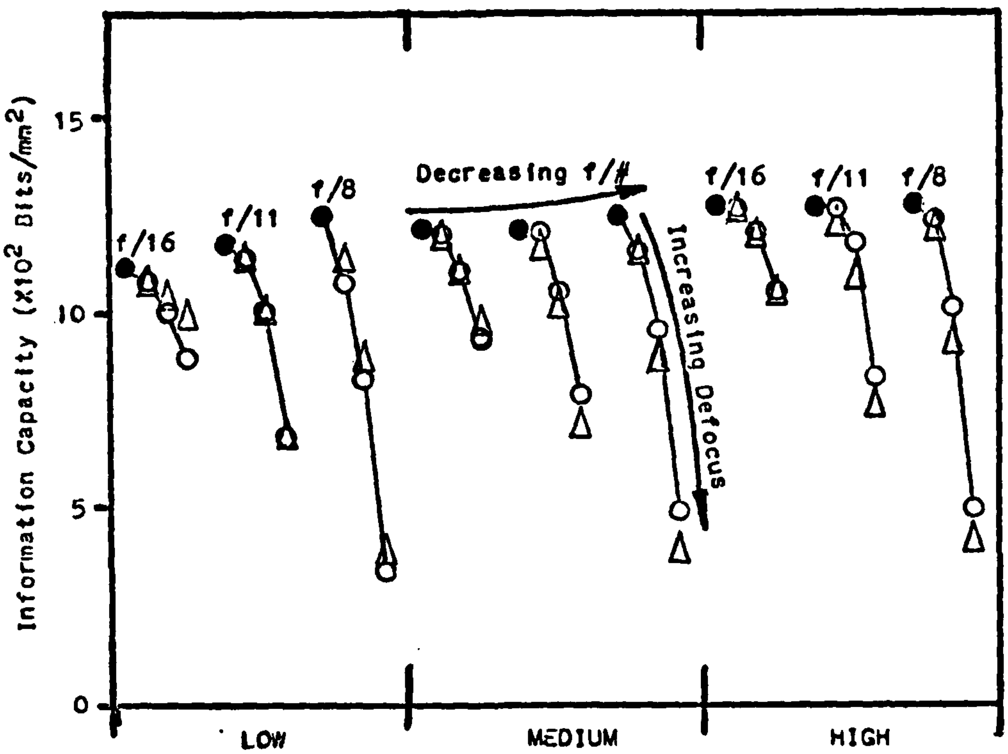


Fig. 16. Information capacities for the Pan-X samples.

● In-focus data
○ Defocus data
△ Defocus predictions

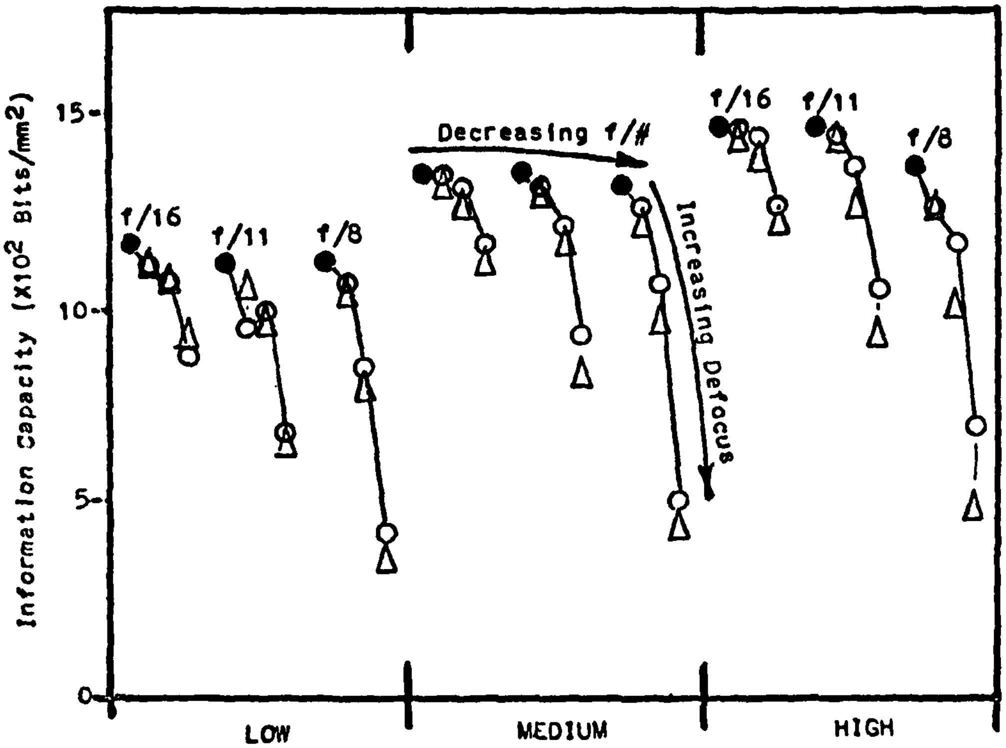


Fig. 17. Information capacities for the Plus-X samples.

● In-focus data
○ Defocus data
△ Defocus predictions

3. CONCLUSIONS

The results have shown that the SNPS method of describing the content of photographic imagery appears to be a valid measure of the content of the image. Further, the predictions of SNPS and information capacity by theoretical means are consistent with the measurements. One can then conclude that the SNPS does measure what is desired. Further, the nature of the measurement is such that it is independent of the specific experimenter or of the optical processor being used, with some reservations regarding the processor-induced noise. This noise can be quantified, if necessary, although this was not done for the comparative information capacity values measured here. The SNPS measurements, when examined in detail, provide an accurate method of describing the average image content, even in the presence of the huge dynamic range of the basic optical power spectrum measurements.

This work, along with the previously reported work, provides a general basis for the application of the signal-to-noise power spectrum methods to quantifying the content of natural scene images. Whichever derived image quality function is appropriate to a particular problem is left to the individual user.

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2. S. F. Sagan, "Measurement of information capacity of photographic images," MS Thesis, University of Arizona, Tucson, Arizona, 1978.

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